Some of the Capabilities and Desirable Features of an "Ideal" Transonic Wind Tunnel

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INTRODUCTION

For several years, there has been an increasing awareness within the United States aeronautical community that the research facilities in this country are not keeping pace with the research and development demands placed upon them. A subcommittee has recently been established under the auspices of the Ground Testing Technical Committee of the American Institute of Aeronautics and Astronautics (AIAA) to make a technical assessment of the wind tunnel capabilities within the United States. As a part of the committee's assessment process, "ideal" wind tunnels are being defined for the various speed ranges to serve as common standards against which the capabilities of our existing tunnels can be compared. The subcommittee was divided into three groups to define "ideal" wind tunnels for three speed regimes: subsonic, transonic, and supersonic/hypersonic. Several individuals and organizations have furnished inputs into the definition of these "ideal" tunnels.

Personnel of the Experimental Techniques Branch of the Transonic Aerodynamics Division of NASA Langley were asked to make a contribution to the definition of the "ideal" transonic tunnel in a survey conducted by the transonic tunnel group. The purpose of the paper is to document, in some detail, the response of the Branch to that survey. Our inputs to this exercise are limited to those areas where we feel at least marginally qualified to make a contribution and provide, if required, a technical defense of our contribution.

SYMBOLS

A	Area of test section
c	Reference dimension for Reynolds number, assumed to be $0.1\sqrt{A}$
C	Any aerodynamic coefficient (Fig. 4)
C_p	Specific heat at constant pressure
h	Enthalpy
M	Mach number
p	Pressure
q	Dynamic pressure, $1/2\rho V^2$
R	Reynolds number+
T	Temperature
V	Velocity
ρ	Density

Subscripts

max	Maximum
min	Minimum
t	Stagnation conditions
∞	Free stream

+ Unless otherwise noted, for consistency throughout this paper, Reynolds number is based on a wing chord equal to 0.1 times the square root of the test-section area. For wings of small aspect ratio, the actual values may be two or three times the value given.

CAPABILITIES AND DESIRED FEATURES

Cryogenic Operation

Operating a wind tunnel at reduced temperatures, first proposed by Margoulis [1,2] in 1920, offers an attractive means of increasing Reynolds number while avoiding many of the practical problems associated with testing at high Reynolds numbers in conventional ambient temperature pressure tunnels. Personnel of the NASA Langley Research Center have been studying the application of the cryogenic concept to various types of high Reynolds number transonic tunnels since the autumn of 1971. The results of a theoretical investigation of the cryogenic wind tunnel concept and an experimental program using a low-speed cryogenic wind tunnel have been reported in references 3 and 4. In order to provide information required for the planning of a large high Reynolds number transonic cryogenic tunnel, a relatively small pressurized transonic cryogenic tunnel was built and placed into operation in 1973. As a result of the successful operation of the pilot transonic tunnel, it was classified by the National Aeronautics and Space Administration in late 1974 as a research facility, re-named the 0.3-m Transonic Cryogenic Tunnel (TCT) and is now being used for aerodynamic research as well as cryogenic wind-tunnel technology studies.

Based on our theoretical studies and on our experience with the low-speed fan-driven tunnel and with the 0.3-m TCT, the cryogenic wind-tunnel concept has been shown to offer many advantages with respect to the attainment of full-scale Reynolds number at reasonable levels of dynamic pressure in a ground-based facility.

Advantages of the Cryogenic Concept. - The effects of a reduction in temperature on the gas properties, test conditions, and drive power are illustrated in Figure 1. For comparison purposes, a stagnation temperature of 322 K (+120^{0}F) for normal ambient temperature transonic tunnels is assumed as a datum. The variation in gas properties with temperature is shown on the left for the condition of constant pressure with the approximate temperature dependence shown with each curve. The corresponding variation in test conditions and drive power are shown on the right for conditions of constant model and tunnel size, constant pressure, and constant Mach number.

It can be seen that an increase in Reynolds number by more than a factor of 7 is obtained with no increase in dynamic pressure and with a large reduction in the required drive power. To obtain such an increase in Reynolds number without increasing either the tunnel size or the operating pressure while actually reducing the drive power* is extremely attractive and makes the cryogenic approach to a high Reynolds number transonic tunnel much more appealing than previous approaches.

Reduced Dynamic Pressure and Drive Power. - Once a tunnel size has been selected and the required Reynolds number has been established, the previously described effects of cryogenic operation are manifested in large reductions in the required tunnel stagnation pressure and therefore in large reductions in both the dynamic pressure and the drive power. These reductions are illustrated in Figure 2, where both dynamic pressure and drive power are shown as functions of stagnation temperature for a tunnel having a 2.5 m by 2.5 m test section at a constant-chord Reynolds number of 50×10^6 at $M_\infty = 1.0$. As the tunnel operating temperature is reduced, the large reductions in both dynamic pressure and drive power are clearly evident and provide the desired relief from the extremely high values that would be required for a pressure tunnel operating at normal temperatures.

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* The tunnel drive power is shown in Figure 1 varying as $\sqrt{T}$ which is strictly true only for an ideal gas. Real-gas calculation of the work done in isentropic compressions at a given pressure and pressure ratio show drive power to decrease somewhat more rapidly than the simple $\sqrt{T}$ variation. In the caluclation of drive power, it is important to use real-gas rather than ideal-gas properites. In particular, one must use the change in real-gas enthalpies, Δh, rather than $C_p \Delta T$ and the real-gas isentropic expansion coefficients [5] rather than the ideal gas specific heat ratios.

Reduced Capital Costs. - For a given tunnel size, both the shell costs, which may account for as much as two-thirds of the total cost of a wind tunnel, and the costs of the drive system for the tunnel, vary nearly linearly with the maximum stagnation pressure of the tunnel. Therefore, for conditions of constant Reynolds number and tunnel size, reducing the tunnel operating temperature results in a reduction of the stagnation pressure. This reduction results in decreased capital costs, even when the somewhat higher costs of the structural materials which are suitable for use at cryogenic temperatures are taken into account.

If the attainment of increased Reynolds number is accomplished by increasing stagnation pressure, a pressure limit is reached for many aircraft configurations beyond which the loads on the model will preclude testing at the desired lift coefficient. With this in mind, an alternate approach to the design of a high Reynolds number tunnel is to establish the maximum usable pressure and allow tunnel size to decrease with design temperature in order to attain the desired Reynolds number. Under these conditions, there is a very strong impact of the cryogenic concept on capital cost due to the large reduction in tunnel size required for the attainment of a given Reynolds number.

At a constant pressure, the cost of the tunnel shell varies approximately with the square of the tunnel size. Thus, a reduction in tunnel size by factor of 5 or 6, which, as can be inferred from Figure 1, may be realized by operating at cryogenic temperatures, represents a substantial savings in capital costs over the much larger ambient-temperature tunnel which would be required to achieve the desired Reynolds number at the same stagnation pressure.

Reduced Peak Power Demand and Total Energy Consumption. - Because of the high peak power demands of large ambient-temperature continuous-flow transonic tunnels, the tunnel designer has usually been forced to abandon the highly efficient conventional fan-driven closed-return type of tunnel and adopt some form of intermittent tunnel using energy storage techniques. However, the reduction in peak power demand obtained by going to conventional energy storage techniques is realized only by accepting an increase in total energy consumpton. The peak power demands and the total energy consumption can both be reduced by adopting the cryogenic tunnel concept which shifts the primary energy consumption from the electric-drive system for the tunnel fan to the cooling system.

In the cryogenic tunnel concept developed at Langley, both the tunnel structure and the stream are cooled by spraying liquid nitrogen directly into the tunnel circuit. Air separation plants, which operate continuously at relatively low power, can be used to produce liquid nitrogen which can then be stored at the tunnel site for use as needed. The cryogenic tunnel thus offers the tunnel designer a system in which the energy stored in the form of liquid nitrogen is used to reduce the drive power requirement rather than provide the drive power directly. Combined with the highly efficient conventional fan-driven closed-return tunnel, this approach greatly reduces the total power consumption, as shown in Figure 3, in comparison with ambient-temperature fan-driven closed-return tunnels, which had been accepted as the most efficient from an energy standpoint. Thus, by reducing the drive-power requirements to a level where a fan drive again becomes practical even for large transonic tunnels, the cryogenic concept not only makes available the many technical advantages of the conventional continuous flow tunnel but, at the same time, also results in significant reductions in the total energy consumed during a test for a given Reynolds number and stagnation pressure. This reduction in total-energy requirement which results from cryogenic operation is especially significant in this age when the conservation of energy is assuming increasing importance.

Unique Operating Envelopes. - The high Reynolds number capability at reasonable model loads and the reduced capital and operating costs are not the only advantages of a cryogenic wind tunnel. Very important additional advantages are offered due to the fact that a cryogenic tunnel with the independent control of Mach number, temperature, and pressure has the unique capability to determine independently the effect of Mach number, Reynolds number, and aeroelastic distortion on the aerodynamic characteristics of the model. In addition, it is possible in a cryogenic tunnel to vary velocity independently of Mach number. This ability offers advantages for certain types of dynamic testing where velocity is an independent test variable [6]. These new and unique aerodynamic testing capabilities may be, in some instances, of equal importance with the ability to achieve full-scale Reynolds number.

In order to illustrate some of these additional research advantages, a typical constant Mach number operating envelope is shown in Figure 4 for a tunnel having a 2.5 m x 2.5 m test section. The envelope shows the range of dynamic pressure and Reynolds number available for sonic testing. In this example, the envelope is bounded by the maximum temperature boundary (340 K), the minimum temperature boundary (based on saturation at free-stream conditions), the maximum pressure boundary (5.0 atm), and the minimum pressure boundary (0.5 atm). Since conventional, ambient-temperature pressure tunnels permit only minor temperature control--being essentially limited to operation along the ambient-temperature line--they encounter large changes in dynamic pressure, and, therefore, large changes in model deformation with changes in Reynolds number.

In contrast, with the cryogenic tunnel with its large constant Mach number operating envelope, it is possible, for example, to determine at a constant Mach number the true effect of Reynolds number on the aerodynamic characteristics of the model without having the results influenced by changing dynamic pressure. (There will be a slight variation of the modulus of elasticity E of most model materials with temperature. To correct for this variation in E, the dynamic pressure q may be adjusted by varying total pressure so that the ratio q/E remains constant over the Reynolds number range.) This ability to make pure Reynolds number studies is of particular importance, for example, in research on the effects of the interaction between the shock and the boundary layer. As indicated on the envelope, pure aeroelastic studies may be made under conditions of constant Reynolds number. In addition, combinations of R and q can be established to represent accurately the variations in flight of aeroelastic deformation and changes in Reynolds number with altitude. Similar envelopes are, of course, available for other Mach numbers.

Maximum Reynolds Number

Establishing the fact that cryogenic operation is a highly desirable feature of any ideal transonic tunnel is considerably easier than establishing the actual value one should choose for the maximum test Reynolds number capability of the tunnel. In fact, one of the fundamental difficulties is to define the level of Reynolds number which is required for valid transonic testing, a problem which has been discussed in several technical papers [7, 8]. Without going into any of the technical details, we would suggest, for the sake of argument, a test Reynolds number for our ideal tunnel of 85 million based on 0.1 x (square root of test-section area) as a reasonable value for near sonic speeds.

Stagnation Pressure

It has been reasonably well established that the highest "usable" stagnation pressure for general purpose testing near sonic speeds is about 5 atmospheres [9]. Since model and sting loads are a function of dynamic pressure, q, arguments can be made that stagnation pressures greater than 5 atmospheres can be used at the lower Mach numbers. Arguments can also be made that the need to match full-scale values of Reynolds number are less critical at low subsonic speeds than at transonic speeds. When capital costs are also considered, it seems reasonable to limit the maximum stagnation pressure for our ideal transonic tunnel to 5 atmospheres.

Selection of a minimum stagnation pressure is not as critical. From a practical point of view, a minimum stagnation pressure only slightly greater than one atmosphere (say 1.05 atm) is perhaps best. However, a wider range of test conditions can be achieved if the necessary pumping equipment is provided to allow sub-atmospheric operation. Therefore, a minimum stagnation pressure of 0.5 atmospheres is reasonable although pressures as low as 0.1 atmospheres are not difficult to achieve in practice.

Stagnation Temperature

A major portion of the "real-gas" studies at Langley related to the development of the cryogenic wind tunnel concept has been concerned with determining the minimum usable stagnation temperature. The phrase "minimum usable," in this case, means as low as possible without getting bad data. The main reason for operating at very low temperatures is shown in Figure 1. As shown in Figure 5, the rate of change of Reynolds number with temperature approaches 2 percent per degree kelvin at the lower temperatures. (It should be noted that the curve in Figure 5 is relatively insensitive to changes in M_∞ or p_t.) When testing at cryogenic temperatures, therefore, it is highly desirable to take maximum advantage of reduced temperatures in order to maximize the benefits of cryogenic operation. This can be done by either taking advantage of the increased Reynolds number for a given stagnation pressure or by reducing the stagnation pressure, and, consequently, reducing the model loads, for a given test Reynolds number. An additional reason to operate at the minimum usable temperature is the reduction in fan-drive power and the corresponding reduction in the amount of liquid nitrogen needed for cooling. It should be noted that as a part of our real-gas studies, theoretical studies have been made which show the thermal and caloric imperfections of nitrogen at cryogenic temperatures to have an insignificant effect on both inviscid and viscous flows [10]. The lower temperature boundary for cryogenic tunnel operation is set, therefore, by the onset of condensation effects rather than any effect of thermal or caloric imperfections.

A conservative approach for selecting the minimum stagnation temperature is to operate at a temperature which avoids any possibility of saturation occurring anywhere over the model. Since the lowest static temperature over a model occurs at the point of maximum local Mach number, a value of T_t can be chosen based on p_t and either the known or anticipated value of the maximum local Mach number in order to keep the local static value of T on the vapor phase side of the saturation boundary. However, such an approach seems to be overly conservative based on experience with airfoils in the 0.3-m TCT and other facilities where condensation effects occur at temperatures lower than those based on maximum local Mach number. Based on the results obtained to date [11, 12, 13], a fairly non-conservative approach to the selection of minimum stagnation temperature seems to be in order. It is assumed, therefore, that a cryogenic nitrogen tunnel can, in general, be operated successfully (i.e., provide good aerodynamic data) at stagnation temperatures which give rise to saturated gas conditions when expanded to the free-stream Mach number.

Test Section Size

Here again, arguments for various size test sections can be made based on convenience, capital or operating costs, and other considerations including past experience. However, having selected for near sonic testing a maximum Reynolds number of 85 million, a maximum "usable" stagnation pressure of 5 atmospheres, and a minimum stagnation temperature such that the flow is expanded to saturation at the free-stream Mach number, it is a relatively simple matter to determine the required test section size.

The simplest method is to use the data presented in Figure 6 which relates the test section size, Reynolds number, and required drive-fan power for various values of stagnation pressure at a free-stream Mach number of 1.0 for stagnation temperatures such that the test-section flow is saturated. As can be seen, for our selected values of R_c, p_t, and T_t, we have fixed the tunnel test section size at 2.5 m x 2.5 m, a reasonable size from many points of view.

Mach Number Range

It is generally agreed that a transonic tunnel should be capable of free-stream Mach numbers between a lower limit of 0.2 or 0.3 and an upper limit of about 1.2. Arguments can be made for extensions of this range at both ends. Since a somewhat wider range is easily within the present state-of-the-art, it seems reasonable for the "ideal" transonic tunnel to operate from essentially zero Mach number, say 0.02, to about 1.3.

Other Desirable Features

Other highly desirable features for the ideal transonic wind tunnel would include a conventional water-air heat exchanger to allow economic operation at ambient temperatures, an adjustable second minimum for the usual beneficial effects on flow quality, a solid adaptive wall test section in order to eliminate wall interference effects (the technology has not yet been demonstrated on a large scale for 3-D), and a magnetic suspension and balance system (MSBS) in order to eliminate support interference effects and take advantage of the numerous other advantages offered by MSBS (again, the technology has not yet been demonstrated on a large scale).

Summary of Capabilities and Desirable Features

A summary of some of the capabilities and desirable features of an ideal transonic wind tunnel are given on the chart presented as Figure 7. The test Reynolds number as a function of Mach number for various operating pressures for this ideal transonic tunnel is given in Figure 8.

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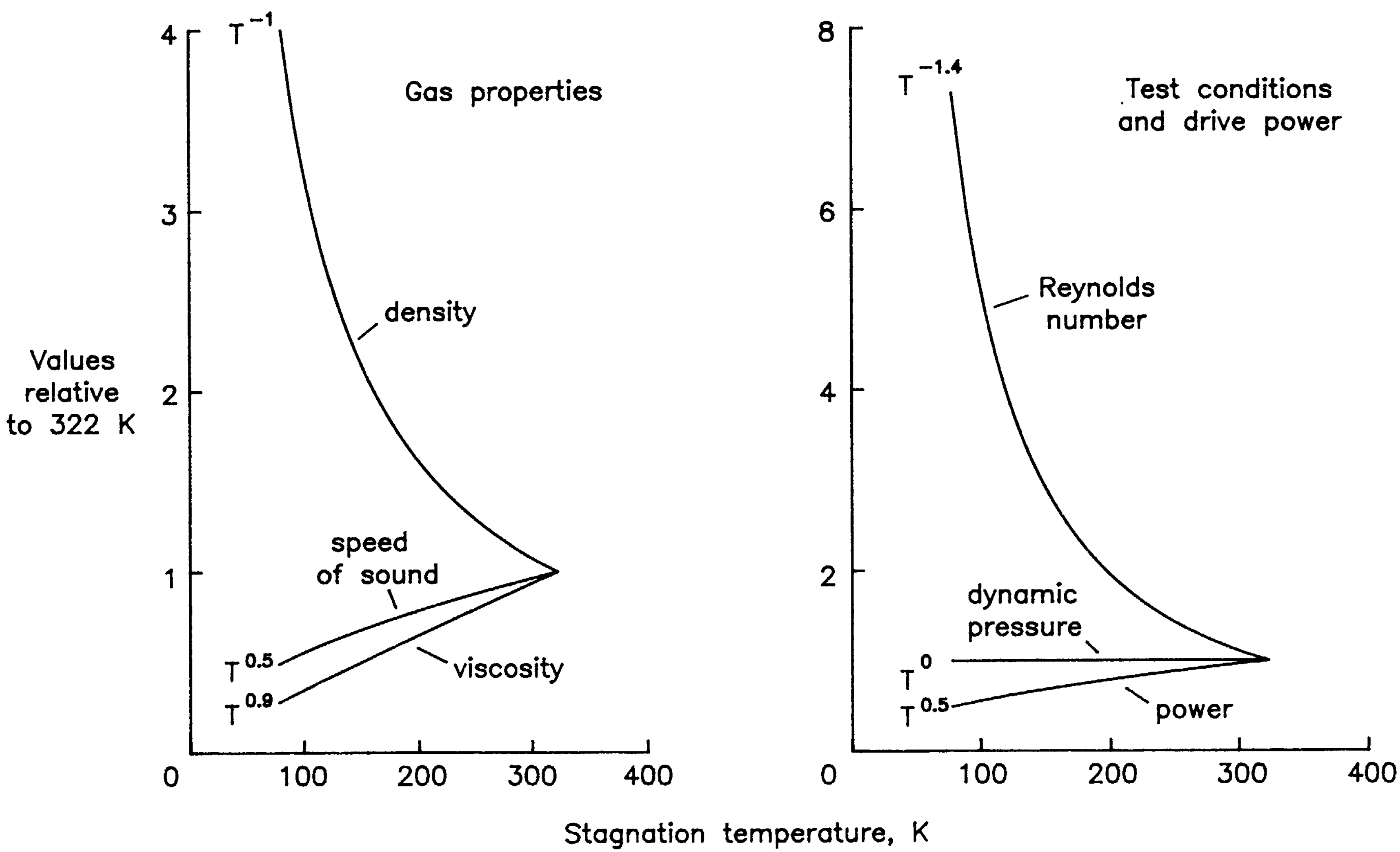

Figure 1.– Effect of temperature on gas properties, test conditions, and drive power for constant model and tunnel size, pressure, and Mach number.

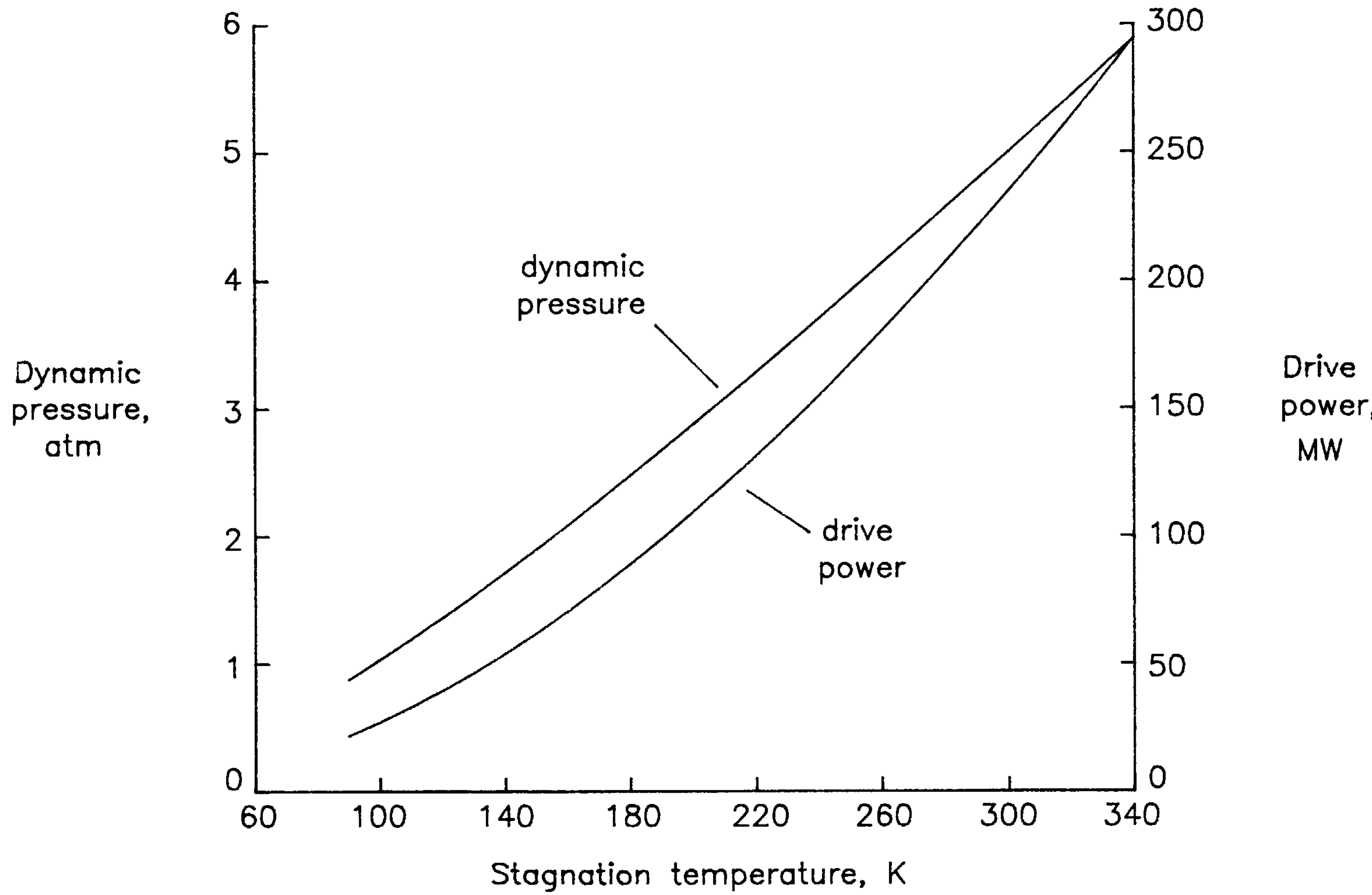

Figure 2.– Effect of temperature reduction on dynamic pressure and drive power for a 2.5 m by 2.5 m test section. $M_{\infty} = 1.0$, $R_c = 50 \times 10^6$.

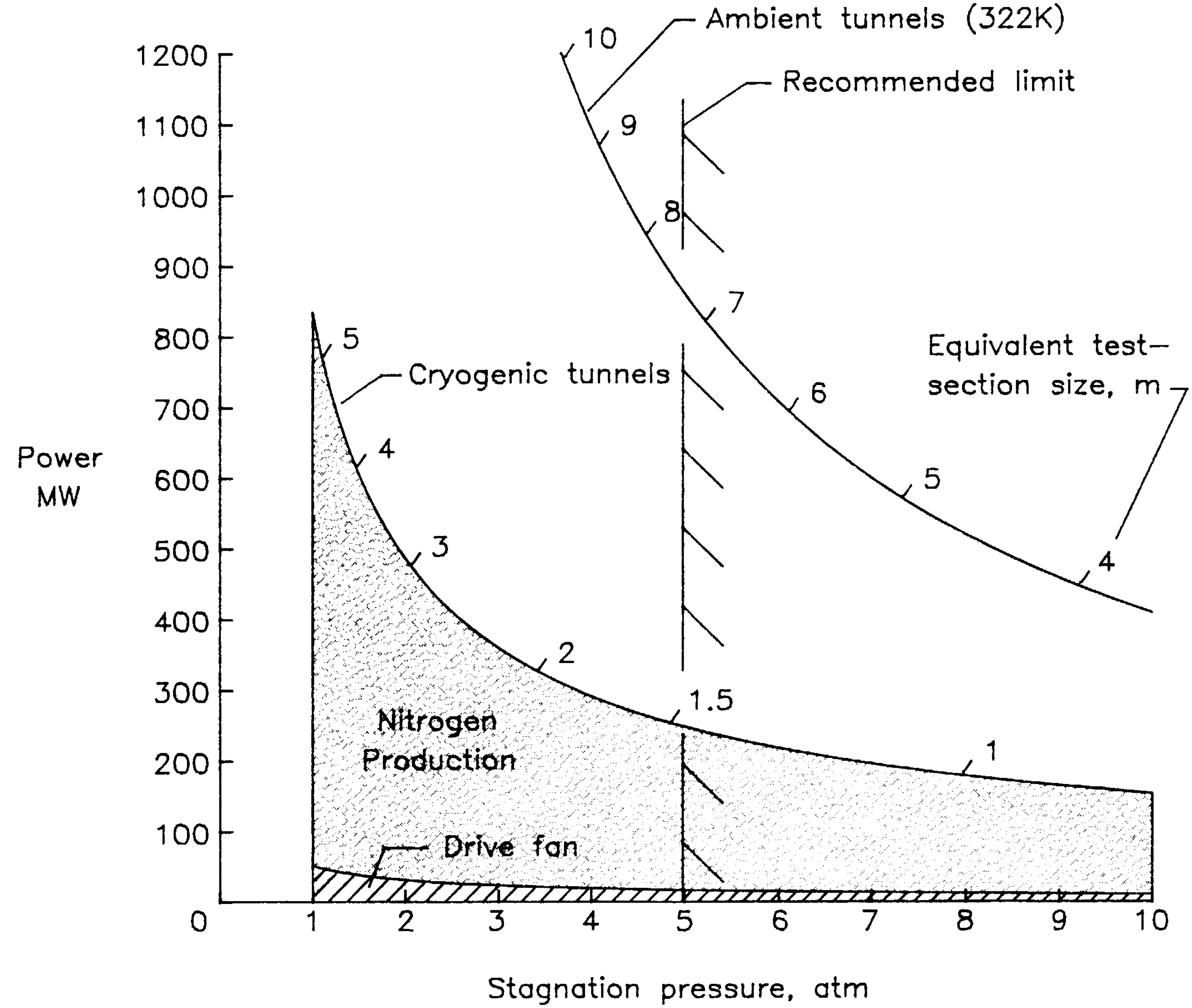

Figure 3.— Total power required for continuous running as a function of stagnation pressure for ambient and cryogenic fan–driven tunnels. $M_{\infty} = 1.0$, $R_c = 50 \times 10^6$.

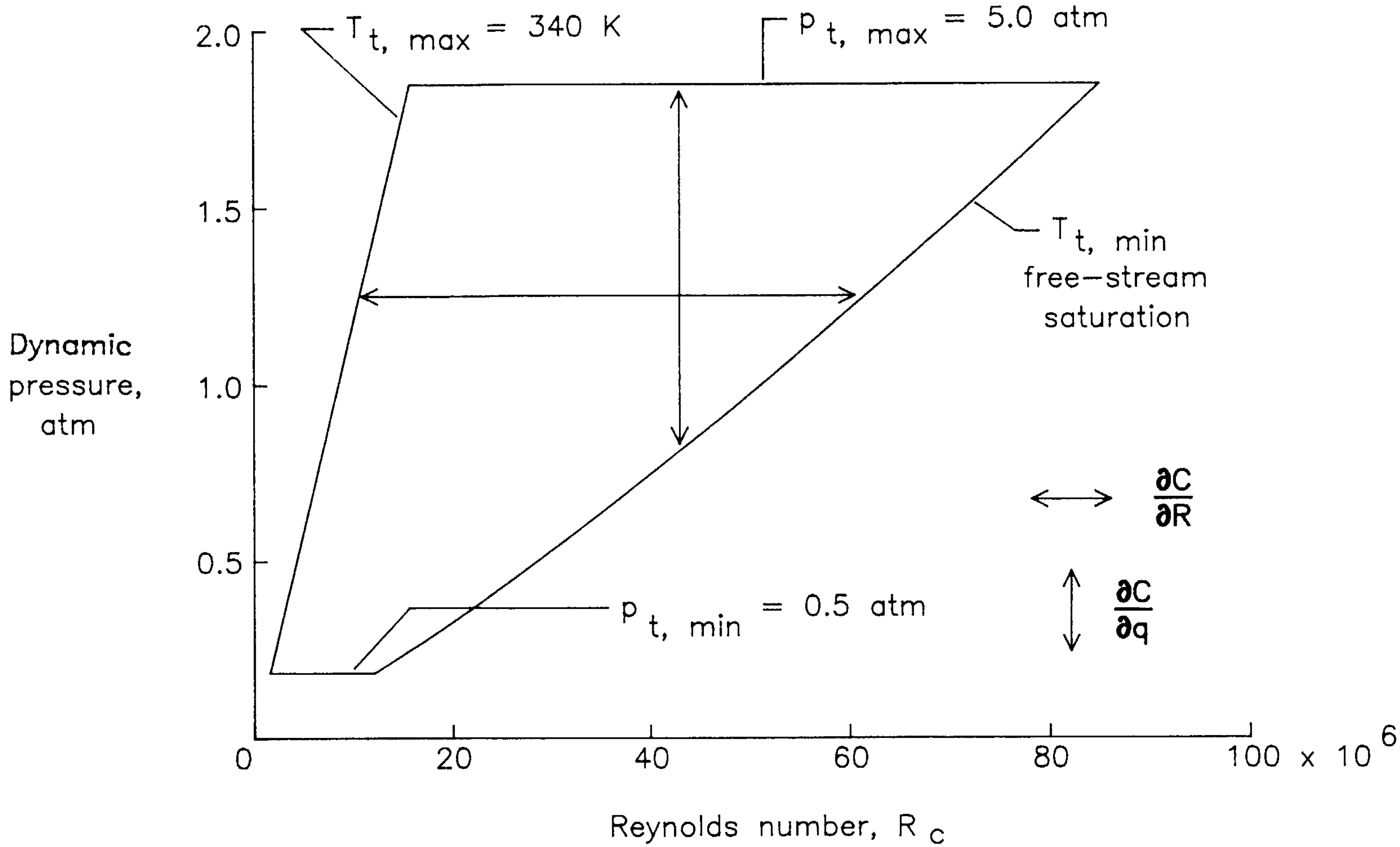

Figure 4.– Constant Mach number operating envelope for a 2.5 m by 2.5 m test section. M_∞ = 1.0.

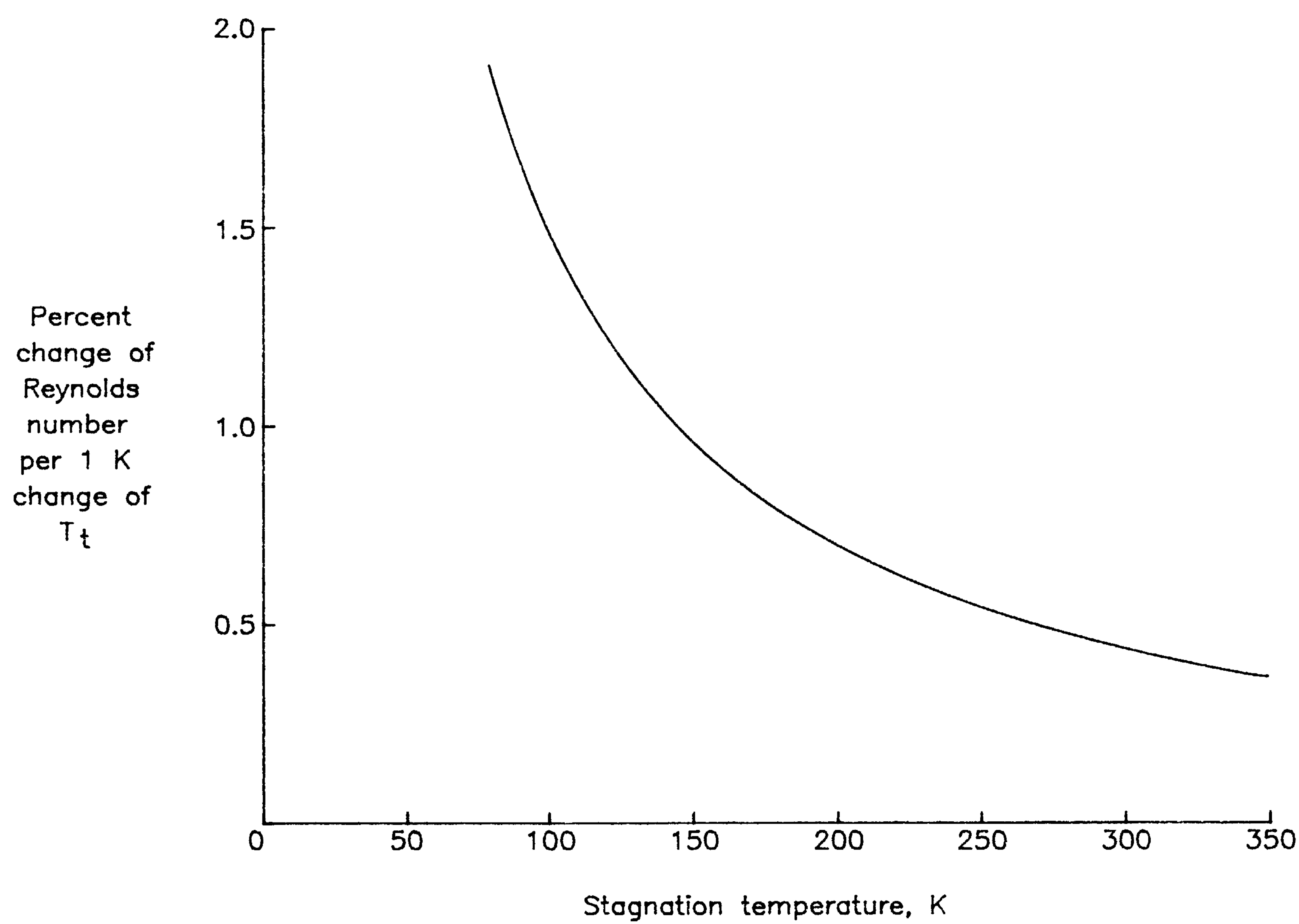

Figure 5.– Change in Reynolds number per 1 K change in stagnation temperature.

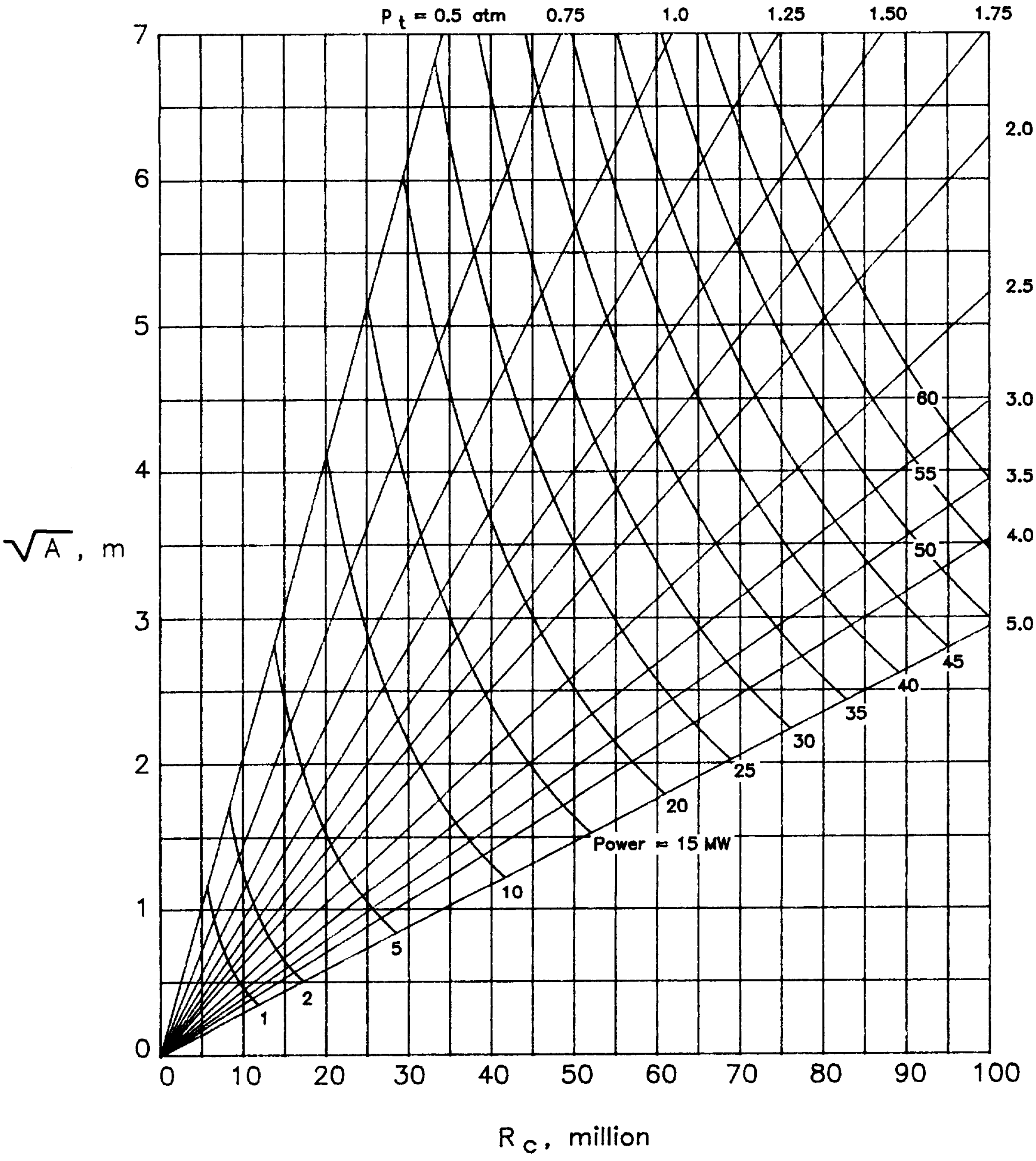

Figure 6.– Performance chart for cryogenic nitrogen tunnel showing relationship between tunnel size, stagnation pressure, drive power, and Reynolds number. $M_{\infty} = 1.0$, $T_t = T_{t,\,min}$.

Some of the Capabilities and Desirable Features of an "Ideal" Transonic Wind Tunnel

Capabilities

* Continuous running (i.e., closed circuit, fan–driven)
* 2.5 m by 2.5 m test section
* p_t 0.5 to 5.0 atm.
* T_t ~77.4 to 340 K
* M_∞ 0.02 to 1.30

  (p_t, T_t, M_∞: Independently variable)
* R_c to 85 million at $M_\infty = 1$

Desirable Features

* Water–air heat exchanger for ambient temperature operation (economy)
* Adjustable second minimum (flow quality)
* Solid adaptive–wall test section (wall interference)
* Magnetic suspension and balance system (support interference)

Figure 7.– Summary of Capabilities and Desirable Features of an "Ideal" Transonic Wind Tunnel.

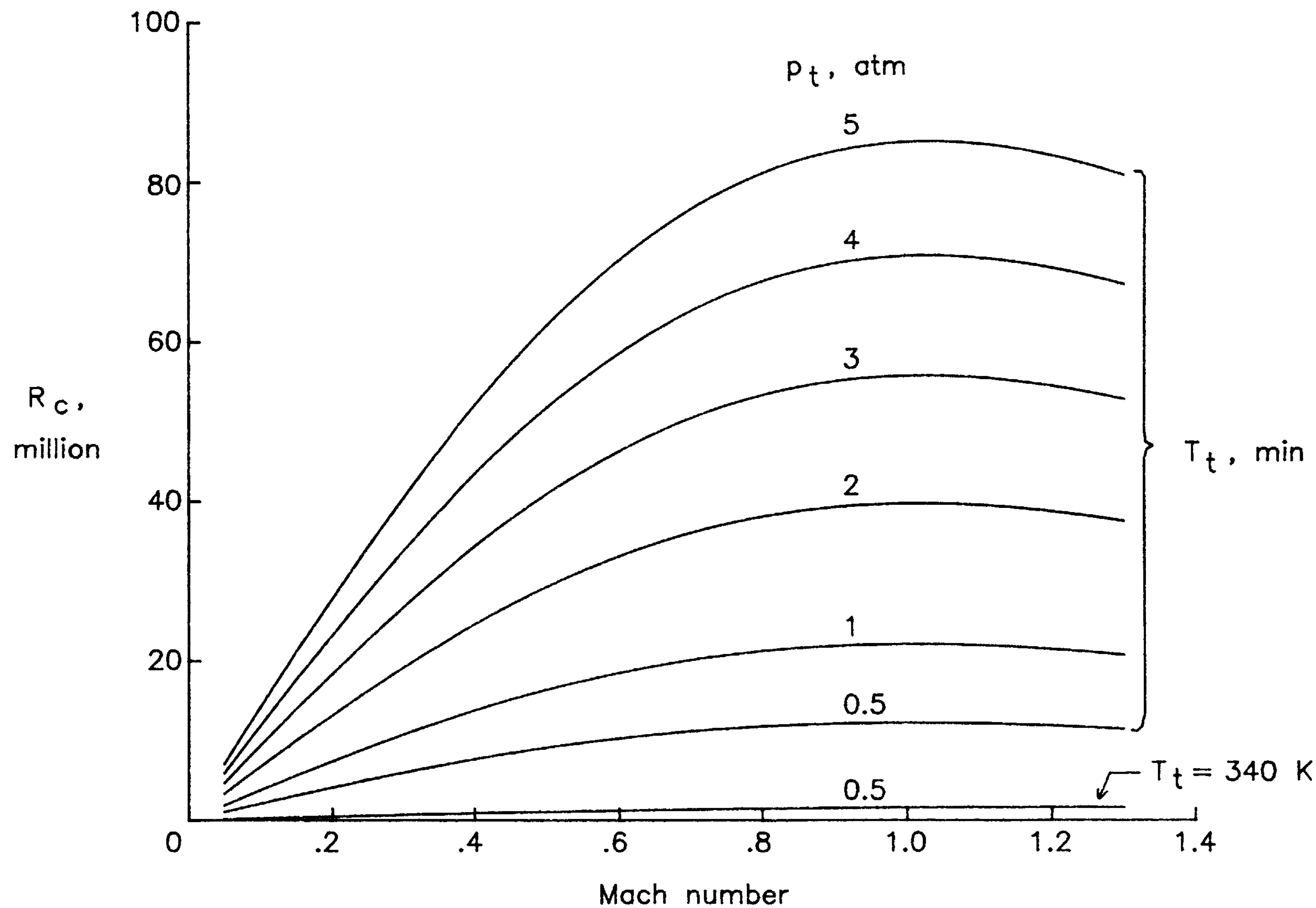

Figure 8.– Reynolds number as a function of Mach number for various values of stagnation pressure for a 2.5 m by 2.5 m test section.